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Review Article

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Developments in Tyre Design for Lower Rolling Resistance:

A State of the Art Review

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Abstract:

Future sustainability of road transportation will require substantial improvement in the efficient use of energy by road vehicles. As new technologies being deployed reduce total vehicle energy consumption, the contribution of tyre rolling resistance to total energy consumption continues to increase. For this reason the tyre's rolling-resistance is starting to drive the focus of many tyre developments nowadays. This is because the rolling-resistance can be responsible for 20-30% of the total vehicle fuel consumption. Thus, lowering the rolling-resistance would help in reducing the fuel consumption (i.e. CO2, NOx and hydrocarbon emissions) and hence improve the environment greatly given the large number of vehicles used globally. It is found that the primary source of the rolling-resistance is the tyre deformational behaviour (i.e. hysteresis damping) which can account for 80-95% of the total rolling-resistance. This paper reviews the state of the art in tyre design, research and development for lower rolling-resistance, with focus on the primary source for the rolling-resistance (i.e. mechanical hysteresis damping), from three perspectives; the structural lay-up, the dimensional features, and the materials compound(s) of the tyre.

Keywords:

Rolling resistance, tyre design, tyre dynamics, vehicle wheels/ tyres, Fuel efficiency/ economy, automotive materials.

1. Introduction:

Extant for over 100 years, the pneumatic rubber tyre is still a dominant solution in Automotive sector for the transport of at least 60% of the population and wares globally.[1] This is due to its reliability and effectiveness in meeting the wide diverse driving functions and requirements of vehicles under various road conditions, which makes it unparalleled in the market.[2,3] However, there are some areas in the pneumatic rubber tyre that still need further improvements and among those; one area, that is attracting a lot of attention and concern due to its importance and impact, is the tyre's rolling resistance.[2,4,5,6]

Basically, the "rolling-resistance" is a phenomenon that is related to tyre rolling over road surface. Traditionally, the rolling-resistance was seen as a longitudinal resistive force to tyre rolling generated because of tyre deformation during rolling, which is a concept limited to steady-state free rolling conditions.[7,8] A more reliable perception of rolling-resistance is looking at it as the mechanical energy losses of the tyre as heat because of tyre rolling for a given distance.[9,10,11]

In general, the "rolling-resistance" occurrence is undesirable to both vehicle performance and environmental welfare. It is found to be one of the main factors opposing the vehicle's mobility, particularly at higher velocities, and leading to energy losses; making the vehicle to consume more fuel to maintain its mobility and produce more CO_2 exhaust emissions in the process, contributing to increasing the air-pollution and the global warming.[8,10-15] Many studies reveal that the tyre's rolling-resistance can be responsible for up to approximately 20%-30% of the vehicle's total fuel consumption depending on the vehicle's type and the driving pattern used, where fuel consumption exhibits nearly a linear change with the change in rolling-resistance.[12,16-20]

As the time passes, the regulations and legislations are becoming more demanding worldwide with regard to the restrictions on the levels of vehicle's CO_2 emissions.[21] The International Energy Agency[22] indicated in 2008 that the move toward lower rolling-resistance tyres is considered to be the most effective way to reduce CO_2 emissions in the transport sector. Globally, the tyre development research is starting to become more rolling-resistance driven and focused.[21,23]

This interest behind improving the rolling-resistance can be seen and understood due to the important and significant role it plays in affecting the fuel consumption and the exhaust emission in return; where lowering the rolling-resistance by about 10% can yield a decrease in fuel consumption by about 0.5-1.5% for light-weight cars and about 1.5-3% for heavy-weight ones.[24-28] Furthermore, the smallest improvement in the tyre's rolling-resistance can create a significant impact on the environmental welfare, in terms of reducing the CO_2 emissions, considering the number of vehicles used worldwide.[29]

According to the current literature, the tyre's rolling-resistance is caused due to three mechanisms that take place in the tyre's environment and those are[8,10,11,14,17,30-34,112-116]:

- The “tyre’s cyclic deformation” which causes some loses in its internal mechanical energy (i.e. strain energy loss). This is due to several occurrences like the reinforcements’ friction and the rubber viscoelastic (hysteresis) property. Among those occurrences, hysteresis damping holds the dominant impact on rolling-resistance making the other occurrences insignificant in contrast (i.e. about 80% to 95% of the total tyre’s rolling-resistance).

- The “aerodynamic drag” due to tyre cutting through the surrounding air as it rotates, which opposes tyre movement and promotes heat transfer between the air and the tyre. Such phenomenon can cause 0% to 15% of the total tyre rolling-resistance depending on the tyre speed.

- The “frictional slip” that takes place when the tyre comes into contact with the wheel rim and with the road surface during its rotation which leads to heat build-up. This is the least important causal factor of the rolling-resistance where it accounts for about only 5% of the total tyre rolling-resistance.

Regardless, the rolling-resistance is not entirely bad as its existence, to some degree, is necessary to achieve other essential functions like good tyre-grip, under proper operational temperature, for traction, cornering and braking.[5,10,29] This is because hysteresis is also largely accountable for the tyre/road adhesion and hence the grip.[117,118,8,14]

This paper aims to provide a state of the art review on the research done on improving the tyre rolling-resistance with focus on the predominant factor causing the rolling-resistance (i.e. tyre deformation (material hysteresis)) in the tyre structural design. This can help in focusing on important areas of tyre development to reduce rolling resistance.

2. Tyre Development for Low Rolling Resistance:

Here, the research work on tyre development is reviewed and categorised into three areas according to the tyre design aspect(s) being used to affect or influence the rolling-resistance in the tyre.

2.1 Via Structure Shape and Build-up:

In this section, the impact of modifying the tyre's body construction on the rolling-resistance is looked at and the findings are summarized in table (1). A key improvement in the area of the tyre's construction was the manufacturing of "radial ply" tyres in 1946 by Michelin.[35] The introduction of "radial ply" tyres instead of the former "bias ply" type provided a significant decrease in the tyre's rolling-resistance that can reach up to around 25% less than the "bias-ply" and in some cases even further less.[19,36,37] Several studies and investigative works provide the same conclusion as indicated in table (1).

Basically, the radial tyres differ from the bias tyres in the ply configuration, with respect to the number used and the direction of carcass plies, and the usage of steel-belts. The radial tyre uses single-layered plies placed radially around its centre with some steel-belts on top, where the bias tyre uses multiple-layered plies placed diagonally around its centre with no steel-belts. This difference in construction provides the radial tyre with a lower inside friction and a more easy cord deflection when subjected to deformation due to

Table (1): Developments in the Tyre’s Body Structure

Study No.	Reference / Source	Tyre's Body Configuration & Construction (Improvement / Change Introduced)	Influence on Rolling Resistance (RR)	Investigation					Remarks
				Method / Approach	Operating Conditions: Speed	Operating Conditions: Vertical Load	Operating Conditions: Inflation Pressure	Others	
1	39	Radial-Ply VS Bias-Ply Constructions	Radial Tyres has lower RR than that of Bias Tyres	Experimental	↑	?	?	48 Radial Tyre Samples and 16 Bias Tyre Samples were investigated	
2	40	Radial-Ply VS Bias-Ply Constructions	Radial Tyre has lower RR than that of Bias Tyre	Experimental	↑	—	—	Radial and Bias Car Tyres on Smooth Flat Surface	
3	37	Radial-Ply VS Bias-Ply Constructions	Radial Tyres has lower RR than that of Bias Tyres	Experimental	↑	—	—	Radial with Bias tyres for both passenger-cars and trucks	The sizes of tested tyres were the same (Labortoray & Road Tests were used)
4	39	Radial-ply Tyres from different Tyre Manufacturers	Clear difference in RR between the tyres of the same construction type	Experimental	↑	**?**	**?**	Radial-Ply Tyres	
5	17	Tyre with Cap-Ply VS Tyre without Cap-Ply	Below ~120kph, Cap-ply tyre causes RR to slightly increase compared to Uncapped tyre. Above ~120kph, Cap-ply tyre leads to significant reduction in RR compared to Uncapped.	Experimental	↑	—	—	Passenger-Car Tyre	According to ISO 8767 standard
6	41	“Belt-width/tread-arc width (belt/arc ratio)”, “rubber thickness above belt-edge (shoulder gauge)”, “rubber thickness underneath belt-edge (insert gauge)”, &“crown angle”	- RR reduction with the decreasing of belt/arc ratio, shoulder gauge & insert gauge. - Crown angle had negligible impact on RR.	Experimental	?	?	?	Four tyre versions each containing twenty-five passenger-car tyres of the same outer size	Investigation on Tyre's Reinforcment Belt geometry
7	42	“Belt/arc ratio”, “crown angle”, “tread radius”, & “tread-arc width/section width (arc/section ratio)”	- RR reduction with decreasing of belt/arc ratio. - Arc/section & Crown angle had negligible impact on RR. - Tread radius had a weak impact on RR compared to belt/arc.	Experimental	?	?	?	Four tyre versions each containing 27 various tyres of different aspect ratios.	Investigation on Tyre's Reinforcment Belt geometry
8	43	Tyres With and Without Tread Patterns	- Pattern-less tyre had 8% lower RR than those with patterns. - Usage of different Tread Patterns had no difference in the impact on RR.	Experimental	?	?	?	The tested tyres were identical.	
9	44	Tyres With Different Tread Patterns	No significant changes found in RR between the different tread-patterns except for the snow tread which had 27% higher RR.	Experimental	?	?	?	Passenger-car tyres	
10	45	Identical Tyres with Tread-Patterns of different block sizes and arrangements	A change of 5% in RR at low speed (40km/h) minimised to less than 2% at high speed (150km/h).	Experimental	↑	?	?	N/A	
11	46	Block Tread Pattern VS Rib Tread Pattern	A block-pattern led to an increase in RR by 15% more than a rib-pattern.	Experimental	?	?	?	Truck Tyres	Block-pattern had a deeper tread of 3 to 5mm
12	47	Stiffness enhanced tread (i.e. by embedding plugs into the tread-cap)	Less deformational energy which led to lower RR	Experimental	?	?	?	The embedded plugs, tread-cap and tread-base come in different materials.	(U.S. Patent 20160001605)
13	48	“Non-pneumatic (Air-free) Tyres” (i.e. Discrete (thin) Spokes Distribution)	- Low RR, inflation maintenance-free, and no flat-run than pneumatic tyres. - Limited to usage with small vehicles of low to moderate speeds for extraterrestrial conditions (& earth too). - It had handling and ride comfort problems.	Experimental	↓	↓	N/A	Made-up from flexible spokes that link the wheel hub to an outer composite shear ring where a rubber tread is mounted	
14	119	Different shapes of Non-pneumatic Tyre's spokes (i.e. Spoke Pairs, Honeycomb, Curved Spokes, & New Curved Spokes)	- The Spoke Pairs model had the lowest RR followed by the Honeycomb model as the 2nd lowest and then the Curved spokes models as the last.	Numerical	—	—	N/A	Quasi-static 2D FE model(s) using Abaqus	Spoke Pairs has the highest vertical stiffness, then the Honeycomb where the Curved Spokes are the lowest.

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↑ : Increase
↓ : Decrease
↗ : Slight Increase
↘ : Slight Decrease
? : Not Stated / Unknown
N/A : Not Applicable

loading/unloading. Such characteristics allow the radial tyre to produce much lower heat and hence less energy losses leading to lower rolling-resistance compared to bias tyres.[16,29,36,38]

Nevertheless, the advantage the radial tyres have over the bias tyres, in terms of having lower rolling-resistance, can be undermined if other elements were not appropriately preserved such as low inflation pressure or inappropriate driving behaviour.[37]

After the "radial" tyre construction, only small improvements have been made to reduce the tyre's rolling-resistance, due to the high cost and the long time involved in the development process, in which those improvements are limited in most cases to the specific tyre(s) examined. An instance on that would be Thompson and Myriam's[39] work on examining the rolling-resistance for a group of radial tyres from various manufacturers in which they found that there is an obvious difference between those tyres in terms of their rolling-resistance regardless being all of similar body construction. This indicates the association of many other design parameters in impacting the tyre's rolling-resistance.

The introduction of "cap-ply" into radial tyres, which is a fabric ply-layer added between the tread base and the steel belts, was found to increase the rolling-resistance slightly, by approximately 2% compared to uncapped tyres, when the tyre rolls below 120kph. This occurs due to the fact that adding the cap-ply means adding extra rubbers/cords weight to the tyre which would dissipate more energy when subject to cyclic loading/unloading. Moreover, the utilisation of a cap-ply would restrict the flexibility of the tyre's shoulders as the crown region would become harder circumferentially causing the crown to be further rounded than in uncapped tyre when the tyre is inflated. However, once the tyre exceeds the 120kph, the cap-ply would have a reverse impact on the tyre rolling-resistance by helping in minimising the rolling-resistance. This is as a result of the cap-ply strengthening the tyre's crown, minimising its curvature deformation in the contact patch area and lowering the effect of the centrifugal forces created during tyre rolling, which leads in the end to help in reducing the increase of rolling-resistance with higher rolling speeds.[10,17]

As indicated in table (1), several investigations on the influence of altering the tyre "belt" geometry on the rolling-resistance revealed that the bigger the belt geometry (e.g. belt/arc ratio, shoulder gauge and insert gauge); the higher the rolling-resistance will be in the tyre. Again, the reason behind such result is that a bigger geometry would lower the belt flexibility and add more mass to the tyre causing, in the process, further energy losses during the deformational hysteresis damping of tyre and higher rolling-resistance in the end. Lindemuth[16] points out that bigger belt geometry, like the usage of wider belts, can provide different impacts on the tyre when its influence is compared to the whole tyre performance. Wider belts can improve the handling, traction and speed capability characteristics of a tyre but on the other hand worsen the rolling-resistance, weight and ride features of the tyre.

To highlight, the investigations on tyre development, especially tyre's construction, can be costly and really time consuming, sometimes with marginal or no gains hence it is not something that can be tried frequently or easily. An example on that would be the researches of both Yurjevich[41] and Walter[42] who spent over a year in investigating and conducting experiments on the impact of belt geometry on rolling-resistance for a group of tyres.

Investigative works on the influence of tyre “tread patterns” on rolling-resistance, like Keefe and Koralek[43] and Williams[44], concluded that the tyres without patterns would have less rolling-resistance compared to the ones with patterns. As for the tyres with different tread patterns, there was no real change in using different patterns on the rolling-resistance excluding the snow tread which gave a higher rolling-resistance. This change may be due to differences in tread compounds between normal and snow tyres. Other investigations, such as Gerresheim[45] and Knight[46], showed a different outcome where there was a change in the rolling-resistance between the different tread patterns investigated. However, Knight[46] suggested this change was due to the different tread patterns having different tread depths, which affected the mass of the tread and hence the rolling-resistance results.

This raises the issue of the inconsistency of experimental settings between the conducted research investigations on a particular aspect of the tyre, which makes it hard to get appropriate and accurate comparative base on the investigated aspect at hand.

A relatively new tyre development was creating a more stiff tread of the tyre by Sandstrom et al.[47] through implanting plugs into the tread top reaching to the tread base, which are all made from different materials. The inserted plugs give the tread more stiffness perpendicularly, reducing the tread vertical deformation during loading/unloading and hence reducing the rolling-resistance while not greatly influencing the other features of the tyre.

An emerging development area that shows some promising advantages compared to the conventional pneumatic tyres is the use of “Air-free” tyres, which provide reduction in rolling-resistance, no run flat and no inflation requirement.[48] Generally, those air-free tyres come with hyper-elastic spokes connecting the wheel hub with an outer shear ring where the rubber tread is fitted on. The spokes with a shear band in the outer ring offer elasticity and less damping in a way that would cause lower viscoelastic energy dissipation and hence less rolling-resistance.[49,50,51] However, this is not always the case as they often show higher rolling-resistance than the pneumatic tyre, especially when discrete thin spokes are used as an air replacement in tyre for loading support and ride comfort achievement, as with the “Michelin Tweel” condition.[119-123] This requires the use of a high number of packed spokes leading to more mass, heat build-up, less vertical stiffness, and hence more deformational distortion.[119-122]

A number of companies have already started exploring the air-free tyre concept from about a decade ago and made some development progress in this field like the Michelin Tweel, Bridgestone 2nd generation, and Polaris Honeycomb.[52] The air-free tyres have been deployed in some uses such as in military and small electrical vehicles but on a limited scale. Further development plans are still in progress and are needed as the existing air-free tyres are yet to match the pneumatic tyres in meeting the wide diverse driving requirements of the large fleet of different vehicles especially in high speeds, extreme conditions, heavy-weight vehicles, and ride comfort. Nevertheless, there have been a number of efforts in further developing the air-free tyres such as Kaufman et al.[53], Ju et al.[50] and Ma et al.[54] for the applications on lunar and passenger vehicles and Rutherford et al.[55] and Narashmhan et al.[56] on lowering the tyre vibrations at high velocities.

2.2 Via Dimensional Features:

In this section, the influence of manipulating the tyre's dimensions on the rolling-resistance was investigated and the results are summarized in table (2).

The current literature uncovered that there are endless ways to modify the tyre's dimensions in order to affect the rolling-resistance. Each way imposes specific alterations to the tyre structure and its characteristics, resulting in different effects on the rolling-resistance based on the tyre at hand. This can be seen in the quite diverse outcomes of the investigative studies on the influence of tyre's dimensions on the rolling-resistance as indicated in table (2). An example on that is the different impact that the tyre's "aspect ratio" (i.e. tyre profile) had on rolling-resistance in studies like Pillai and Fielding-Russell[57], Gerresheim[45], Clark[58], and Walter[59]. Furthermore, there are the vast chances of interventions and conflicts between many design-parameters of the tyre against each other, when attempting new tyre design, in terms of the material composition(s), body configuration(s), and dimensional settings. Such clash makes it unavoidable for some trade-off to occur between the tyre’s characteristics, among which is the rolling-resistance.

Table (2): Developments in the Tyre's Dimensional Settings

Study No.	Reference / Source	Tyre's Dimensional Settings						Wheel Diameter	Investigation					Influence on Rolling Resistance (RR)	Remarks
										Operating Conditions					
		Aspect Ratio	Section Width	Section Height	Outer Diameter	Inner Diameter	Tread Depth		Method / Approach	Speed	Vertical Load	Inflation Pressure	Others		
1	57	↑	↕	—	—	—	?	—	Both Analytical & Experimental	?	—	—	Radial Passenger-Car Tyres	→	
2	45	↓	?	?	?	?	?	?	Experimental	?	—	—	Passenger-Car Tyres	→	
3	60	↓	↕	?	—	↕	?	↕	Experimental	↓	?	?	Radial Truck Tyres / Fixed Material Compound & Construction	↘	
4	61	↓	↑	—	—	—	?	—	Experimental	?	?	?	Passenger-Car Tyres / Fixed Material Compound & Construction	↓	
5	46	↓	?	?	?	?	?	?	Experimental	?	?	?	Radial Truck Tyres	↓	
6	62	↑	?	?	—	?	?	?	Analytical Modelling	?	?	?	Radial Passenger-Car Tyres	↕	Minimum RR at 70% Aspect Ratio
7	63	?	—	?	↕	—	?	—	Experimental	?	?	?	Fixed Material Compound & Construction	?	Minimum RR at 85% Aspect Ratio
8	64	?	?	?	—	?	?	?	Experimental	?	—	—	Passenger-Car Tyres	?	Minimum RR at 65% Aspect Ratio
9	58	↑	↓	—	—	—	—	—	Semi-Empirical (Analytical + Experimental)	?	—	↑	Truck Tyres / Fixed Carcass thickness & Tread thickness	↓	Inflation Pressure has greater impact on RR than Section Width
10	58	↓	↑	—	—	—	—	—	Semi-Empirical (Analytical + Experimental)	?	↑	↑	Truck Tyres / Fixed Carcass thickness & Tread thickness	↓	Inflation Pressure has greater impact on RR than Section Width & load
11	65	?	↑	?	?	—	?	—	Experimental	↓	—	↑	N/A	↓	Inflation Pressure & Speed have greater impact on RR than Section Width
12	58	—	↓	?	↑	?	—	?	Semi-Empirical (Analytical + Experimental)	?	—	↑	Truck Tyres / Fixed Carcass thickness & Tread thickness	↓	Inflation Pressure & Outer Diameter have greater impact on RR than Section Width
13	59	↑	↓	↑	—	↓	?	↓	Experimental	↑	?	?	2010 Volkswagen-Golf car UHP Radial Tyres of the same brand & type	↓	Faster Rolling (from 0 60mph)
14	57	↑	—	↑	↑	—	?	—	Both Analytical & Experimental	?	—	—	Radial Passenger-Car Tyres	↓	
15	57	↑	—	↑	↑	↑	?	↑	Both Analytical & Experimental	?	—	—	Radial Passenger-Car Tyres	↓	
16	57	↑	—	↑	↑	↓	?	↓	Both Analytical & Experimental	?	—	—	Radial Passenger-Car Tyres	↓	The Increase in Section Height is more than the Decrease in Wheel Diameter
17	57	↑	—	↑	—	↓	?	↓	Both Analytical & Experimental	?	—	—	Radial Passenger-Car Tyres	—	The Increase in Section Height is equal to the Decrease in Wheel Diameter
18	17	—	—	—	↑	—	?	—	Experimental	↓	?	?	Radial Passenger-Car Tyre	↓	According to ISO 8767 standard of testing
19	66	?	?	?	↑	?	?	?	Experimental	?	?	?	Under different Road Surfaces	↓	Outer Diameter has greater impact on RR in Soft Surfaces compared to Harder Surfaces
20	39	?	?	?	↑	?	?	?	Experimental	↓	?	?	Radial Tyres	↓	
21	60	?	?	?	?	?	↓	?	Experimental	?	?	?	Truck Tyres	↓	Linear Relationship between RR & Tread Depth
22	46	?	?	?	?	?	↓	?	Experimental	?	?	?	Various Truck Tyres	↓	Linear Relationship between RR & Tread Depth
23	67	?	—	?	?	—	↓	—	Experimental	?	↕	↑	Radial Passenger-Car Tyres	↓	
24	68	?	—	?	?	—	↓	—	Experimental	?	?	?	Radial Truck Tyres	↓	Non-Linear Relationship between RR & Tread Depth
25	69	?	—	?	?	—	↓	—	Experimental	?	↕	↕	Low Profile Radial Truck Tyres	↓	Non-Linear Relationship between RR & Tread Depth

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In addition to the tyre's design parameters, there are the tyre's operational parameters (e.g. speed, inflation pressure, and normal load) that can have a significant impact on the rolling-resistance as illustrated in table (3). Those parameters can influence, remarkably, the effects of the tyre's dimensions on the rolling-resistance in case they were not properly maintained or cautiously taken into account during designing and testing. As indicated earlier, the inconsistency of experimental settings is another cause for the quite mixed results of the impact of tyre's dimensions on the rolling-resistance. Similar conclusions are reached by Schuring and Futamura[20] and LaClair[10].

For an example, underinflated tyre would lead to larger tyre deformation and friction as it rolls, causing greater heat losses (i.e. rolling-resistance), tread-wear, and improper contact.[124-130] Pressure monitoring and self-inflation systems are growingly being developed and used to address such an issue. Currently, those systems are used in many military and commercial vehicles (e.g. Tiremaax-Pro, MTIS, and TPCS) whereas for consumer vehicles just the monitoring systems are widely used.[126-129,131-134]

Such focus on the commercial vehicles, for self-inflation systems, may refer to the significant impact they have on fuel economy and the capabilities of commercial vehicles in terms of their large tyre sizes with higher inflation pressures, load-carrying capacity and long travelling distances along with having the room to accommodate the systems, which commonly come with compressor, sensors and other parts.[29,125,130] Adding to the complexity, the optimum tyre pressure is not fixed as it depends on the driving and environmental conditions which the consumer vehicles are more sensitive to.[124]

Table (3): Impact of Operating Parameters on Tyre's Rolling Resistance

Study No.	Reference / Source	Investigation: Method / Approach	Operating Conditions: Speed	Operating Conditions: Vertical Load	Operating Conditions: Inflation Pressure	Operating Conditions: Others	Tyre's Parameters: Aspect Ratio	Tyre's Parameters: Section Width	Tyre's Parameters: Section Height	Tyre's Parameters: Outer Diameter	Tyre's Parameters: Inner Diameter	Tyre's Parameters: Tread Depth	Wheel Diameter	Influence on Rolling Resistance (RR)	Remarks
1	20	Mathematical & Experimental	?	↑	—	Radial Passenger-Car Tyre (Tested on a standard roadwheel)	—	—	—	—	—	—	—	↑	
2	70	Numerical (Coupled Thermomechanical Finite Element model)	?	↑	—	Passenger and Radial Medium Truck Tyres	—	—	—	—	—	—	—	↑	Numerical & Experimental
3	71		?	↑	—	Passenger Radial Tyre	—	—	—	—	—	—	—	↑	Numerical & Experimental
4	72		—	↑	—	Radial Tyres	—	—	—	—	—	—	—	↑	
5	17	Experimental	—	↑	—	Passenger Car Tyres	?	?	?	?	?	?	?	↑	According to ISO 8767 standard
6	11	Both Analytical & Experimental	—	↑	—	Passenger Radial Tyre & Radial Truck Tyres	—	—	—	—	—	—	—	↑	According to SAE procedure J1269
7	28	Experimental	—	↑	—	Radial (FR78-14) Tyre	—	—	—	—	—	—	—	↑	
8	73	Numerical (Experimental & Thermal Modelling)	—	↑	—	Radial Tyre	—	—	—	—	—	—	—	↑	
9	74	Numerical (Finite Element Modelling) with Experimental Validation	—	↑	—	Radial Passenger-Car Tyre	—	—	—	—	—	—	—	↑	
10	20	Mathematical & Experimental	↑	?	?	Passenger-Car Tyres / On Dry & Wet Road Surfaces	?	?	?	?	?	?	?	↑	
11	17	Experimental	↑	—	—	Passenger-Car Tyre	?	?	?	?	?	?	?	↑	According to ISO 8767 standard / RR increases sharply after 120 km/h
12	75	Experimental	↑	—	—	(7.50-14) Tubeless Tyre	—	—	—	—	—	—	—	↑	RR increases sharply after 120 km/h
13	40	Experimental	↑	—	—	Radial and Bias Car Tyres on Smooth Flat Surface	?	?	?	?	?	?	?	↑	RR increases sharply after 120 km/h
14	73	Numerical (Experimental & Thermal Modelling)	↑	—	—	Radial Tyre	—	—	—	—	—	—	—	↑	
15	74	Numerical (Finite Element Modelling) with Experimental Validation	↑	—	—	Radial Passenger-Car Tyre	—	—	—	—	—	—	—	↑	RR increases sharply after 120 km/h
16	20	Mathematical & Experimental	?	—	↑	Radial Passenger-Car Tyre (Tested on a standard roadwheel)	—	—	—	—	—	—	—	↓	
17	70	Numerical (Coupled Thermomechanical Finite Element model)	?	—	↑	Passenger and Radial Medium Truck Tyres	—	—	—	—	—	—	—	↓	Numerical & Experimental
18	71		?	—	↑	Passenger Radial Tyre	—	—	—	—	—	—	—	↓	Numerical & Experimental
19	72		?	?	↑	Radial Tyres	—	—	—	—	—	—	—	↓	
20	17	Experimental	—	—	↑	Passenger-Car Tyre	?	?	?	?	?	?	?	↓	According to ISO 8767 standard
21	11	Both Analytical & Experimental	?	—	↑	Passenger Radial Tyre & Radial Truck Tyres	—	—	—	—	—	—	—	↓	
22	66	Experimental	↕	?	↑	Under different Types of Road Surfaces (Medium Hard Soil & Concrete)	?	?	?	?	?	?	?	↘	For Soft (Sand) Surface, the increase in Pressure causes the RR to increase too.
23	28	Experimental	—	—	↑	Radial (FR78-14) Tyre	—	—	—	—	—	—	—	↓	
24	73	Numerical (Experimental & Thermal Modelling)	—	—	↑	Radial Tyre	—	—	—	—	—	—	—	↓	

Table Key Indicato

— : Fixed, Constant, Remain Unchanged or No Change	↑ : Increase	↘ : Slight Decrease
→ : Almost No Change or Marginal Change (i.e. Negligible)	↓ : Decrease	? : Not Stated / Unknown
↕ : Variable or fluctuating (with no particular	↗ : Slight Increase	**N/A** : Not Applicable

Nevertheless, there are two promising designs where the whole self-inflation system is contained within the tyre/wheel assembly. Although they are oriented toward the commercial vehicles and not widely applied yet, on-going efforts are in place for the consumer vehicles application too.[125,126,128,130,133,135,136] These concepts are the Goodyear AMT, like Coda SIT, (i.e. Inflation through tyre's peristaltic pumping) and the Aperia Halo (i.e. Inflation through pendulum-type pump activated by tyre rotation).[128,130,131,134,136-138]

Accordingly, there is the urgent requirement to have a quantitative description that would cover the relationship between the rolling-resistance and the dimensions of the tyre, including tyre's other related features, in an overall and accurate manner for better tyre designing with minimum trade-offs. This is since the existent researches in the field are yet to achieve that especially with the complexity of the tyre where numerous design factors are involved and their relationship with the rolling-resistance is needed to be examined both separately and in combination given all the potential configurations that the tyre can take. Moreover, generally, automobiles and tyres producers do not share their related information and data on tyre designing and its association with rolling-resistance for confidentiality purposes.[76]

Such circumstances dictate the need for on-going, wide and steady course of research work on the tyre rolling-resistance which would normally demand a lot of time, collaborative efforts and resources. This is to explore new possibilities for development and attempt to address current drawbacks for more improved tyre rolling-resistance. Both Clark[58] and Juhala[29] shared similar recommendations to this in their research works.

Regardless of the current research state, there are a number of useful consistent findings. For instance, the modifications, which require expanding the targeted tyre's dimension(s) further, would lead to increasing the rolling-resistance in most cases such as expanding the tread width or depth as indicated by several studies like Treichel[60] and Bosik et al.[69] in table (2). Simply, this is because bigger dimension means more rubber mass to deform and hence more energy losses (i.e. rolling-resistance) due to hysteresis damping. Contrarily, for the tyre outer diameter, it has been found that bigger outer diameter(s) would help noticeably in further lowering the rolling-resistance.[10,17,29,57,58,66] This comes about as the outer diameter is interrelated to the zone size of the tyre's contact patch and in turn to the vertical load on the tyre and, by being longer, it would provide the tyre with more strength and lower bending deformation at the contact patch at the same vertical load, leading to lower mechanical energy losses.[17,29]

There is an emerging shift toward the development and usage of high profile (i.e. taller and slimmer) tyres by vehicle and tyre producers like "Fiat Chrysler" which is working on developing promising high profile tyres to help in lowering the rolling-resistance and the compromises with other tyre features such as weight, braking and handling.[77] However, other producers prefer using low profile (i.e. shorter and broader) tyres to gain an improved performance with respect to steering, cornering, grip, traction, and braking but at the cost of negatively impacting the rolling-resistance and the ride comfort.[17,78] The high profile tyres provide performances which are contrary to this.

Using either low or high profile tyres will always include some sort of compromises between the tyre features as indicated earlier. An emergent idea, that may significantly minimise the compromise that exists between the usage of low and high profile tyres, is the usage of “variable tyre profile” that would allow the tyre to dynamically shift between low and high profiles whenever required, based on the driving conditions. Such a concept is already under investigation by “Goodyear” since 2015 as it looks forward to developing a “triple tube” tyre in the future.[79]

Nevertheless, this concept is still at the design stage and yet to be made and applied practically as the current literature does not offer any real investigative researches on the subject. If it is to be made real successfully, the “variable tyre profile” would offer a more effective approach to tackle the different vehicle requirements, with respect to the drive performance and the fuel consumption, since the existent literature provides constant modifications only to the tyre profile which are quite inefficient in meeting the various requirements mentioned earlier as they need different dimensional features from the tyre.

2.3 Via Materials:

This section looks at the effect of altering the tyre material(s) on the rolling-resistance in which the findings are summarized in table (4).

Across the literature, the tyre materials are found to be a major research area with a large base of findings and continuous development work. This is due to the tyre material hysteresis being held as the major cause of the rolling-resistance (i.e. 80%-95% of rolling-resistance) as indicated previously. Mainly, the automobile’s tyres are built from “rubber components” and “reinforcement cords” that require more than 200 raw materials, which

Study No.	Reference / Source	Tyre's Material(s) (Improvement / Change Introduced)	Influence on Rolling Resistance (RR)	Investigation: Method / Approach	Operating Conditions: Speed	Operating Conditions: Vertical Load	Operating Conditions: Inflation Pressure	Others	Remarks
1	28	Usage of different tread polymers	Polymers ranked from having low to high RR respectively: Natural rubber, cls-polybutadiene (BR), solution styrene-butadiene (SBR), emulsion styrene-butadiene (SBR), polybutadiene (BR), polyisoprene (IR) and butly.	Experimental	—	—	—	Radial Passenger-Car Tyres of the same size, tread design & tread hardness.	All treads had the same composition percentage of carbon-black and aromatic-oil
2	84	The shoulders and the central portion of tyre tread have different polymers	Lower RR and Better Traction (grip)	Experimental	—	—	—	Radial Passenger-Car Tyres of the same size	According to ISO 28580 / US Patent 20160016435
3	85	Variation of tread material contents / ingredients (i.e. Polymer, carbon-black, oil and curatives)	A decrease in dry-traction by 5% and wet-traction by 7% at 30km/h to 15% at 100km/h for a 10% decrease in RR.	Experimental	↑	?	?	N/A	
4	86	A tread material with different hysteresis properties at different temperature and frequency ranges where RR and traction occur	Tread material to offer low hysteresis at low temperatures & frequencies for low RR. The opposite for better traction	Analytical	?	?	?	For RR, at (~50°C) and (~10-150Hz). For wet traction, at (~100-150°C) and (~50kHz - 1 MHz).	Based on the occurrence of grip and RR at different temperatures and deformational frequencies
5	61	A tread material with a close glass-transition temperature to that of traction domain	Tread material to provide high loss-tangent at low temperatures for higher traction and the opposite for	Analytical (time-temperature superposition principle)	?	?	?	For frequency range of 1 to 110 Hz, at 50 to 70 °C for RR and at -20 to 20 °C for	
6	87								
7	88								
8	88	Modification to Polymer's Macrostructure: Decreasing chain-end concentration through reducing molecular weight distribution	Decrease the material hysteresis and hence RR too	Experimental	?	?	?	Manipulate molecular weight distribution by blending polymers with different molecular weights	
9	89							Different molecular weight distribution by blending various monodisperse polymers	
10	90							Usage of Random Branching to change molecular weight & its distribution	
11	91	A better dispersion of carbon-black	significant minimization in RR	Experimental	?	?	?	Increasing the interaction between polymer-chains and carbon-black via	
12	92								
13	20								
14	17	Reduce reinforcing filler concentration in rubber compound(s) (i.e. widen distance between the filler aggregates).	Minimize the energy dissipation and the RR	Experimental	?	?	?	A) Minimising filler volume without changing the filler aggregate size or vice versa. B) Improving the filler distribution in the rubber compound.	Approach (A) has limited room for improvements. Approach (B) causes the manufacturing process to be more difficult and expensive.
15	93	A "nano-molecular base" for tyre's cap-ply.	Enhance grip and minimise heat dissipation and RR too.	Experimental	?	?	?	Nokian's WR-A3 tyre	
16	93	A nano-coating for tyre tread.	Lower heat dissipation and therefore RR.	Experimental	?	?	?	Bridgestone's Ecopia tyre	
17	93	Tyre with carbon Nano-tubes.	Enhance tyre's mechanical properties like tensile strength (by ~600%) and hardness (by ~70%) leading to lower tyre's deformation compared to SBR tyres.	Experimental	?	?	?	N/A	
18	94	Nano-meter Silica, as fillers, for improved distribution with styrene butadiene rubber-compound.	Better grip and RR	Experimental	?	?	?	Giti Radial Champiro UHP Tyres	
19	34	Usage of different cords reinforcement materials (i.e. for carcass & belts)	- Aramid carcasses and belts had a significant impact on lowering RR. - Rayon carcasses caused higher RR. - The rest of materials did not exhibit major differences on RR.	Experimental (Cost Down & Constant Speed Wheel Testing)	—	—	—	HR78-15 Poly-steel Radial tyres of the same design	Tested materials: Carcass (i.e. aramid, nylon, rayon, polyester and fiberglass). Belt (i.e. steel, aramid and fiberglass)
20	34	Usage of different reinforcement's (carcass and belt) weight	Increase in weight would normally lead to significant increase in RR.	Experimental (Cost Down & Constant Speed Wheel Testing)	—	—	—	HR78-15 Poly-steel Radial tyres of the same design	
21	95	Usage of "electro-rheological fluid (ERF)" as a smart filler for two types of tyre polymers (i.e. "Electrospun polymer Fabrics" and "silicon rubber")	Adjustable tyre viscosity (internal dampening) and hence tuneable RR.	Experimental (using Wood Pendulum Acoustic Emission Device)	N/A	N/A	N/A	For ERF reinforced electrospun polymer(s), ERF/PVDF (Polyvinylidene fluoride) and ERF/PCL (Polycaprolactone) were studied.	

Table Key Indicato

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↕ : Variable or fluctuating (with no particular Pattern)	↗ : Slight Increase	**N/A** : Not Applicable

Table (4): Developments in the Tyre's Materials make the tyre of a complex build, to attempt meeting the various driving conditions and requirements.[80,81]

The current literature tackles the development of the tyre materials for low rolling-resistance from two perspectives; one is seeking low hysteresis rubber materials and the other is looking for reduced tyre deflection by amending the reinforcement cords.[7,34,38] The emphasis of the research work has been toward the first perspective (i.e. rubber components) since it has a predominant influence on the rolling-resistance compared to that of reinforcement cords.[28,34]

For the rubber materials, the “tyre’s tread” holds the majority of the research interest and focus for decreasing the rolling-resistance and improving the traction grip.[10,20,29,82] This is because the rubber part of the tyre tread, apart from having a big mass, has been shown to be responsible for most of the hysteresis energy losses (i.e. ~70%) compared to other parts of the tyre (i.e. Sidewall (~15%) and Beads (~15%)).[10,28,83]

In the area of tyre rubber developments, many approaches were investigated as illustrated in table (4). One of the early approaches was the usage of “diverse polymer types” for the tread which proved that the diverse polymer types would have various effects on the rolling-resistance too, with the natural rubber having the least rolling-resistance among the other polymer types.[28] Several researches were then done based on the approach of “tread polymer macrostructure” which involved improving the rolling-resistance through lowering the polymer chain-end concentration by either decreasing the molecular weight distribution, reducing chain branching, or increasing the primary chain’s number-average molecular weight (i.e. total molecules weight / total molecules number).[20,88,89,90] Another way was through the chain-end coupling to enhance the carbon-black spreading via raising the interaction between the polymer chains and the carbon-black.[91,92]

Yet another approach was the suggestion to design a “tread polymer microstructure” with a glass transition temperature and frequency that would provide a low rolling-resistance and a good traction grip respectively at their relevant temperatures and frequencies as they occur at different ranges and both of them are necessary for efficient tyre operation.[10,20,61,86,87,88,96,97] Hence, it is necessary to ensure that the microstructure design would keep a good equilibrium of the tyre’s properties like the glass-transition temperature, the hysteresis-damping, and tensile strength to have proper tyre rolling-resistance and traction.[97-100] Nonetheless, altering the polymer microstructure is not a simple task as it would affect the macrostructure as well, where the macrostructure is found to have a much greater impact on the rolling-resistance compared to that of microstructure.[20,89,90,101]

More recently, lowering the “filler chemicals concentration” in the tyre’s rubber composite is an alternative approach that has been tried to reduce the rolling-resistance.[10,17] This was done through increasing the spaces between the filler aggregates by either lowering the filler volume fraction and leaving the filler aggregates size the same, performing the opposite to the earlier procedure, or making the filler distribution more uniform in the rubber composite. A flourishing development area is the approach of implementing “Nano particles” into the material construction of various tyre parts to enhance their characteristics especially with regard to reducing the rolling-resistance.[29,93,94] This includes the use of a nano molecular base for the cap ply and a nano coating for the tread to reduce the heat losses, carbon nano tubes to improve tyre's tensile strength and stiffness, a nano clay to enhance the inflation air containment inside the tyre, and nano meter silica-fillers to enhance their distribution within the tyre rubber composite.

"Intelligent or smart materials" approach concerns the utilization of materials with integrated sensor, actuator, and control unit to detect a particular signal (e.g. electricity or magnetic field) in the environment, respond to this signal by a prearranged behaviour (e.g. shape or damping change), and revert to their original state when the signal is off.[5,102-106] This field is not fully transparent but yet it is a fast developing area with a large scale of potential uses in tyre operation because of the promising abilities such materials hold especially with the trend toward automation in vehicles nowadays.[106,107] Nevertheless, presently, the only effective tyre application it is used for in the market is the tyre pressure sensor(s), which comes normally with a piezoelectric material, while many developments are still in the laboratory stage due to technical obstacles like manufacturing difficulties, interferences in work mechanism, communication problems, durability, cost, and reliability.[108] Chen's[95] laboratory development of smart fillers for the tyre polymers is an example on that as shown in table (4).

For the tyre "reinforcement cords", the utilisation of diverse cord materials was found to have different effects on the rolling-resistance with the Aramid material having noticeable influence on reducing the rolling-resistance and the Rayon material having a contrary influence. Furthermore, increasing the mass of the tyre cords was found to raise the rolling-resistance as well.[34]

In general, the development research on the tyre's materials is found to have the least degree of design flexibility or freedom among the other development areas of the tyre (e.g. dimensional and body structure features) in which it is very difficult to make substantial development changes.[28,83] This can be attributed to a number of reasons. First are the inevitable compromises that occur between the rolling-resistance and the other tyre characteristics (e.g. traction grip, wear resistance, and cushion) when the tyre materials are subject to change to achieve specific vehicle requirements.[20,109] Secondly, it is extremely hard to produce a tyre rubber composite that would accommodate low rolling-resistance and other conflicting characteristics (e.g. excellent grip or improved wear resistance) as this would require dissimilar material properties and manufacturing requirements.[10,17] Lastly, the complexity of the type and the size of the relationships between the rolling-resistance and the other tyre design and operational parameters make it problematic and hard to specify the rolling-resistance via analytical analyses. This leaves the specification of the rolling-resistance almost relying on experimental work alone, which tends to be very costly and time-consuming with little outcomes in return.[109] However, increasingly, numerical simulation is being utilised to help in defining the rolling-resistance, which provides a reasonable assessment tool.[20,110,111]

3. Summary and Conclusion:

In this review, the researches on the tyre designs for low rolling-resistance were looked at from three perspectives; the structural build-up, the dimensional features, and the materials compound(s). It has been found that the tyre distortion at the contact-patch zone is principally responsible for the rolling-resistance. In other words, the larger the contact-patch zone and the greater the tyre distortion; the higher the rolling-resistance generated in the tyre. Furthermore, aside from the tyre design, the tyre operational parameters are found to have a great impact on the rolling-resistance (i.e. normal load, rolling speed and inflation pressure) that their input need to be taken into account in tyre designing for low rolling-resistance.

A key obstacle encountered in the tyre development is reducing the rolling-resistance without a trade-off with the other tyre main performance characteristics. This tends to be a very difficult and nearly non-achievable task because of the interference and the complexity of the relationship of the rolling-resistance with many of the tyre's operational characteristics required to meet the broad and diverse targeted functions of the tyre. Such a challenge has made tyre designing for low rolling-resistance analytically unreliable hence the only option left is the costly trial-and-error experimental investigations. However, numerical solution is now increasingly being used to assist with the experimental tyre designing to lower the costs. Another effect of this challenge is that, usually, the developments achieved in lowering the rolling-resistance may be restricted to the particular tyre type and design used in the development.

Nevertheless, there are a number of the tyre development approaches which have proven to have nearly consistent and obvious impact on reducing the rolling-resistance. Compared to the tyre design parameters, the tyre's operational parameters were found to impact more consistently and have bigger influence on the rolling-resistance besides having a wider range. In terms of the design parameters, the developments of tyre materials have the slightest degree of design flexibility among the other tyre design aspects.

Generally, there are several growing trends of research developments found to attract increasing interest and hold promising potentials/gains in lowering the rolling-resistance. The "non-pneumatic (air-free) tyres" are one of those growing trends which is a concept involving cutting down and re-distributing the mass in the tyre's structure. This trend is yet to be as effective and reliable as the conventional pneumatic tyres in meeting the full vehicle operational requirements. Another promising trend is the "variable tyre profile" which is a concept that aims to allow the tyre to change its aspect ratio dynamically during rolling. This concept is yet to be extensively researched, experimentally investigated, and practically tried.

Moreover, the usage of "Nano technology" in enhancing the properties of tyre materials is another growing trend with many new possibilities yet to explore. A much wider and promising trend is the "intelligent materials" which involves the use of sensors, Nano materials, magnetic materials, and more to further automate the tyre structure to self-function more effectively as the situation dictates. This is a challenging trend with many growing targets to achieve and infinite options of potential material resources and arrangements to use. The increasing use of numerical simulation can only help in speeding up the investigation of these new technologies and reducing costs in the development of a new generation of tyres needed to ensure the sustainability of road transportation.

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